

SNS ELECTRICAL DISTRIBUTION DESIGN

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1. INTRODUCTION

The cost of power quality problems can be very high and include the cost of downtime, loss of experimenter confidence, and, in some cases, equipment damage. The recovery of lost data, including reentry and reverification, can be very expensive indeed. The unpredictability of this disruption to operations aggravates the problem, and significant management intervention is often required to ensure that recovery operations are carried out logically and efficiently to restore accelerator operation as quickly as possible.

The term “good power quality” can be used to describe a power supply that is always available, always within voltage and frequency tolerances, and has a pure noise-free sinusoidal wave shape. “Poor power quality” describes any supply that deviates from this ideal; whether or not the deviation is important depends entirely on the purpose of the installation, the design of the equipment, and the design of the installation. Poor power quality may be apparent as supply interruptions, voltage dips, transients and noise, harmonic distortion, or ground leakage.

Power problems arise primarily from two causes: interruptions in the public supply and deficiencies in the customer’s installation. On average, the public supply will be unavailable for about 100 minutes per year, but it is frequently blamed for the many other problems that really arise from installation of the accelerator.

Electricity is a very expensive fuel, and as much as 10% of the electricity bought by industry is wasted by the use of inefficient plants and poor installation practices. Efficiency can be greatly improved at no cost by careful plant selection and good installation design. Well-planned installations, taking into account the types and numbers of loads, with due allowance for load growth, will have substantially reduced incidence of problems and lower running costs over the whole life of the installation. These benefits will be gained with little or no increase in initial installation cost.

New problems are arising in electrical installations in today’s high-density accelerator technology, largely caused by the quantity of electronic equipment in use. The potential costs to accelerator operations of power failures and disturbances can be very high indeed, and managers need to understand the risks and know how they can be assessed and reduced.

Some risks, such as a failure in the supply distribution system, are outside the direct control of the user, but it is important to realize that the impact of such a failure can be reduced if appropriate measures are taken in the design of the installation. Risk reduction may require provision of an uninterruptible power supply, a local standby generator, a second redundant feed from the Tennessee Valley Authority (TVA) electrical distribution grid, or a combination of any of these. Both are being implemented at SNS and are balanced against the potential risk. In safety-critical or data-critical operations, where the cost of the potential disruption is considered high in terms of human life, lost data, and therefore operational impact, even high-cost solutions will be fully justified.

Other risks arise from the design of the user’s installation, the specification of the electrical plant, or the type of equipment required by the nature of the accelerator operations activity. The layout of the cabling and cross-sectional area of the conductors must be and is specified with harmonic generating loads in mind so that interference and overheating cannot result. Separate circuits are provided for klystrons and heavy motor loads in the central helium liquefier (CHL) so that switching that produces transient spikes and starting current, that causes voltage dips that can adversely affect other, more

sensitive, equipment is almost completely eliminated. Some magnet power supplies, radio-frequency (RF) equipment, and computer equipment—in short, most modern electronic equipment—make use of switched mode power supplies. These are smaller, lighter, and more efficient than traditional transformer units but have the major disadvantage that they generate high levels of harmonic currents in the main electric power supply. Where a number of computers are installed, these harmonic currents can reach high levels, especially in the neutral of three-phase supplies, leading to overheating and the risk of fire. Such equipment also produces earth leakage currents that have serious safety implications in many installations and that could cause interference and data loss in communications systems.

A well-designed electrical system will also take energy efficiency into account. Not only should high-efficiency plants, such as energy-efficient motors and transformers, be selected, but best-practice, low-loss installation standards should also be applied. Often this means using conductors that are two standard sizes larger than the minimum size for thermal safety suggested by national codes. Although the larger cable is more expensive to purchase, the total installation cost is only slightly increased and the outlay is quickly recovered in lower electricity bills.

The reliability of the electrical installation is the base for accelerator availability. Reliability predictions became a common practice in accelerator technology. Topics such as redundancy, resilience, and parallel paths are introduced, as well as the principles behind reliability in electrical power distribution systems.

The concept of reliability became important when the complexity of systems began to increase rapidly as the electronic content grew. The development of advanced weapons systems and the early work on electronic computers stimulated the study of reliability. More recently, with the application of complex electrical and electronic systems in the telecommunications, nuclear, and space industries, a complete new science of reliability has emerged. In the context of this, we are concerned only with reliability as it is applied to the power distribution system and not with the equipment it powers.

The reliability expectations of power distribution systems have increased because of the critical nature of some of the systems supplied and the high costs associated with failures. For example, loss of power to an air traffic control installation or a medical system could be life threatening, and it is common for such sites to have a standby power supply of some sort.

In the case of SNS accelerator systems, power loss to a computer data processing system can incur high costs because of data loss and long recovery periods. The larger the computer system, the longer the recovery period will be after a power supply disruption; for some of the larger installations, this can be seven hours or more. This is not meant to imply that they are the only important types of installation; the Personnel Protection System (PPS) is also affected by power failure, resulting in lost accelerator operation time, and PPS recertification could take 12 hours or more. However, since computer systems are central to accelerator operations, they are used as an example that most managers and engineers will easily relate to.

Computer systems are notoriously sensitive to poor quality main supplies, and the electronic data processing (EDP) power supply specification is much tighter than any primary or secondary main supply specification. Tolerances for durations of less than 10 ms are typically as follows:

Voltage: $\pm 5\%$

Frequency: $60 \text{ Hz} \pm 1\%$ (i.e., 59.4 to 60.6 Hz)

For computer systems, the requirements are as follows:

No deviation or break	>15 ms
Spike free	>1 kV
Total harmonic voltage distortion	<10%
Voltage, steady state	$\pm 1\%$
Frequency, dynamic	$\pm 1\%$
Slew rate (rate of change of frequency)	<0.5 Hz/second

Neutral-ground potential difference $<5\text{ V}$

No electricity supplier could provide a public supply that meets these specifications at an economic price, so the user must install suitable power conditioning and distribution equipment to provide the required level of security. Of course, the extra equipment will contribute an unreliability of its own, which must be taken into account.

2. AVAILABILITY

A major consideration for system designers and users is service availability, that is, the proportion of time that adequate service is provided. Availability must be carefully specified; the power supply availability might be 0.999886, equivalent to one hour total nonavailability in one year, but the system availability will be less because of the time required to reestablish operations.

As an example, for a computer network requiring 7 hours to reboot and restore, a single 1-hour interruption per year would result in a nonavailability of 8 hours—an overall availability of 0.9991. If the power supply failed for 10 seconds every day—equivalent to 1 hour per year—then the nonavailability would be 7 hours per day, or 2,555 hours per year—an availability of only 0.71. Although the availability of the power supply has not changed, that of the system has been seriously reduced by the frequency of supply interruption. Although the former scenario might be tolerable for some operations, the latter would certainly be totally unacceptable for SNS. Although availability is an important specification, it does not tell the whole story and must be interpreted carefully.

3. RELIABILITY, RESILIENCE, AND REDUNDANCY

Reliability is a measure of the probability that a component or system will remain operational for the required lifetime. Methods of calculating overall reliability from that of the individual components are given as

$$R(t) = N_s/N_o(t) ,$$

where $R(t)$ is the reliability function, N_s is the number of components surviving, and N_o is the number of components installed.

$$Q(t) = N_f/N_o(t) ,$$

where $Q(t)$ is the failure probability function, N_f is the number of failures, and N_o is the number of components installed.

Resilience is the ability of a system to remain operational after the failure of at least one of its components. Usually this is achieved by providing parallel paths so that failure of one of them does not cause the whole system to fail; that is, at least one path is redundant in normal operation. Because a resilient system must experience more than one failure before becoming unserviceable, overall system reliability is improved. If good maintenance procedures are in place, a failure in the redundant path should be repaired well before a second failure occurs.

The objective of modern installation design is to provide a continuous supply to critical loads. In most situations, the steps taken to achieve this will include some of the following:

- Provision of a separate, independent supply from the grid.
- Provision of a standby generator.

- Provision of an uninterruptible power supply.
- Dualling of the distribution system, including any local transformers, busbars, etc.
- Separation of critical and noncritical loads.
- Provision of maintenance facilities to enable servicing without removing power from critical loads.

4. THE IMPORTANCE OF RELIABILITY ASSESSMENT

Improving reliability will always involve some additional expenditure because, for example, redundant paths require additional cabling and equipment and high-reliability equipment could attract premium prices. There will be many routes to achieving a particular level of reliability for an installation, and each will have an associated cost. Selecting the optimum approach requires a careful analysis of the site requirements; the financial, business, and safety risks posed by failure; and the cost of each solution.

An understanding of reliability principles will allow systems to be designed for specific degrees of reliability and service availability by, for instance, using appropriate amounts of redundancy. System designers and planners can make informed decisions about the tradeoffs between reliability and costs and can allocate the reliability requirements among the various elements of a system in order to minimize overall costs.

As technology advances and solid-state devices replace electromechanical devices, it is generally assumed that new systems will be more reliable than their predecessors. However, the increasing complexity of solid-state systems means that there are many more components involved, each of which has a finite reliability. The probability of failure must be minimized by careful design and by introducing redundant elements arranged so that they can take over until the faulty elements have been identified and repaired.

The purpose of the reliability assessment is to accomplish the following:

- Provide an early indication of the potential of a system to meet a stated reliability requirement.
- Reveal aspects of the design that require particular attention to reliability or that present high risks in relation to the requirements.
- Provide as a basis for reliability apportionment (e.g., for use by subcontractors whose subsystems are required to meet reliability requirements delegated to them) and to establish the reliability required of an item.
- Provide inputs to studies that could influence product design, such as design reviews, design evaluation, tradeoff studies, life cycle costing, maintenance support, logistics studies, and safety analysis. For example, assessment could highlight particular areas where an acceptable relaxation in performance could produce a major saving in life-cycle costs.
- Establish whether the production process has adversely affected reliability.
- Establish whether an item in service has performed or is performing with the reliability required and whether it is likely to continue performing adequately for the remainder of its generated life.
- Contribute to safety studies of an item (it is necessary to distinguish between the operation and the safety requirements for reliability).
- Estimate and control the effects of design changes on reliability.
- Provide input to logistic support analysis, spares ranging and scaling, hazard analysis, and related maintenance studies.

In any assessment, it is important to present the information results clearly with any limitations and assumptions clearly identified. Reliability assessments are an aid to good engineering but cannot function alone. The designer must carefully interpret the results to ensure that the optimum solution is achieved.

5. BENEFITS OF RELIABILITY ASSESSMENTS

Reliability assessments enable system designers and planners to make informed judgments and decisions about the

- choice of system configuration,
- manufacturer of the equipment,
- type of components/equipment,
- interface to other equipment,
- tradeoffs between reliability and cost, and
- choice of system that best meets SNS requirements.

The assessment provides a failure probability figure for the system based upon known or estimated statistical failure rates for each component. It does not indicate that the system will not fail more frequently, but rather it is a guide to the average reliability. No manufacturer can provide a lifetime guarantee for the reliability of their products!

6. ASSESSING RELIABILITY

The following are some of the factors that contribute to the difficulty of assessing reliability accurately.

- Inconsistency in manufacture—not all components will have exactly the same lifetime.
- Consequential damage (or overstressing) of a component caused by partial or catastrophic failure of another.
- Incomplete repair (e.g., components that were overstressed by the failure of another and were not replaced, resulting in a shortened lifetime).
- Poor replacement (e.g., replacement components that are not of same quality as originals).
- Failures not being accurately reported and therefore not included in statistics.
- Environmental factors (e.g., systems run at higher temperatures will experience shorter lifetimes).
- Problems caused by poor maintenance (e.g., failure to keep air vents clear will cause local hot spots and result in earlier failure).

7. UNCERTAINTY IN ASSESSING RELIABILITY PREDICATIONS

It is important to appreciate that reliability predictions are subject to uncertainty. This arises from a number of factors:

- There is an inherent uncertainty in transferring failure (or success) data to different applications and environments.
- It might be unclear what constitutes a failure in various situations.
- The effect of human actions and interpretations might be uncertain.
- Predications are naturally based upon historical data. Differences in technology, changes in design team personnel, and the changing specification of the product all introduce possible sources of error into predictions.
- The rate of occurrence of failure might not be constant with respect to time.

- Predication methods often have to be oversimplified in order to make problems tractable.
- Confidence limits exist with respect to the statistical data being assessed.

8. APPLICATION OF RELIABILITY ASSESSMENTS

Reliability assessments are an aid to good engineering, and consideration should be given to the following:

- Well-proven engineering practices should be used.
- All statistical information should be assessed to a common base.
- Previous designs and processes should be reviewed to determine the capability of the new product.
- Statistical analysis should always be tempered by engineering judgment. Parallel redundancy, for example, can be introduced to improve the overall probability of successful operation of a system, but it might not be effective if the same inherent fault mechanisms exist within the parallel items.

Reliability is the product of the component count and the number of redundant paths that will allow the product or system to perform satisfactorily until the faulty elements have been repaired. Therefore, the less complex the system, with fewer components and more redundant paths, the more reliable the system will perform without loss of power.

9. AVAILABILITY AND MEAN TIME TO REPAIR

The average time needed for repairs is known as the mean time to repair (MTTR), which must be taken into account when calculating availability. Repair times need to be considered when using the mean time between failures (MTBFs) to estimate the effective reliability of the system.

In practice, the MTTR can depend on a whole range of factors, including the following:

- Time needed to learn about the fault.
- Time needed to locate the fault.
- Time needed to isolate the fault.
- Time needed to gain access to the fault.
- Access to the service engineer and time needed to reach site.
- Availability of (and delivery time of) spare parts.
- Time needed to repair the fault and to make any necessary adjustments and perform tests.

The availability of a system or component is the proportion of time for that it operates correctly. It is the ratio of operational time to total time, which is the sum of the operational and repair times:

$$\text{Availability} = \text{MTBF} / (\text{MTBF} + \text{MTTR}),$$

where MTBF is mean time between failures and MTTR is mean time to repair.

System users are sometimes more concerned with the availability rather than the reliability of such systems. It is usually important to maximize the proportion of time a system is available, and this can involve tradeoffs between component reliability and repair time. For instance, hard-wired components are usually much more reliable than plug-in ones because of the relatively high failure rates of connections. On the other hand, the repair times of plug-in components might be much shorter than those for hard-

wired ones because they can simply be replaced. Hence, the use of plug-in components can result in higher availability but with a higher failure rate. The optimum balance depends on the absolute values of MTBF and MTTR.

The application of reliability includes the following:

- Power system design philosophy
- Parallel redundancy and standby modes
- Maintainability
- Cost versus reliability
- Reliability and safety

10.POWER SYSTEM DESIGN PHILOSOPHY

In designing any power distribution system, the following fundamental elements should always be addressed:

- Reliability
- Resilience
- Maintainability
- Capacity
- Flexibility

The parameters for providing a reliable electrical system include the following:

- Use of modular standby equipment rather than a large central plant.
- Individual power supplies rather than shared power supplies to the critical load.
- Dual feeds (parallel paths) throughout the electrical distribution system with automatic changeover on failure.
- Use of redundancy and no-break switching for power distribution, standby generating equipment, and the UPS concepts.

With information available regarding reliability, capacities, maintainability, and costs, a suitable scheme can be selected to meet the specification parameters.

In general, the overall reliability of a system is dependent upon the number and reliability of individual components; a more complex system impairs reliability as more components are involved, leading to a greater number of failure points. Therefore, the use of high-quality reliable components based on "tried and tested" technology that has undergone an appropriate service period is essential.

11.PARALLEL REDUNDANCY AND STANDBY MODES

Redundancy is a useful method of increasing reliability and optimizing the balance between operation effectiveness and expenditure. In the context of reliability, redundancy signifies that a system will continue to function satisfactorily in spite of the failure of some of the component parts. This resilience to failures is obtained by providing alternative paths of operation, by arranging selected elements of the system in parallel.

11.1 STANDBY REDUNDANCY

Standby redundancy means that an alternative means of performing the function is provided but is inoperative until needed; it is switched on upon failure of the primary means of performing the function. An example of standby redundancy would be use of a standby generator in a building to ensure continuity of supply in case of a mains failure. The generator is not called for until it is needed when the power supply fails. Such a scheme would not be suitable for a computer system because data would be lost during the relatively long period required to start the standby generator.

11.2 ACTIVE OR PARALLEL REDUNDANCY

In active or parallel redundancy, all redundant units are operating simultaneously rather than being switched on when needed. The most obvious approach is to use two components, each capable of carrying the full load so that if one should fail the other will take over—this is referred to as 1 + 1 redundancy. An alternative approach is to split the load among a number of units, each capable of carrying only a fraction of the load, and provide just one additional redundant unit—this is referred to as N + 1 redundancy. For very critical loads, more than one fully rated redundant unit may be provided. For example, a 1 + 2 redundancy scheme would have two fully rated redundant units supporting the single operating unit and would require all three units to fail before the system fails. Because there is no interruption, active redundancy is suitable for computer installations.

11.3 N + 1 AND 1 + 1 REDUNDANCY

The theory of redundancy is that if a component within a system fails, the system will continue to function because alternative paths are available for the system to operate. In each case, the first number refers to the number of components required for the system to function correctly and the second number refers to the number of standby components available. It is possible to have many redundant components that would significantly improve the reliability of the system. However, this would also be expensive, and in most applications a balance is achieved between reliability and economics.

12.MAINTAINABILITY

Maintainability is the probability that a device will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures [3]. Generically, there are four parts to achieving good reliability:

1. Detecting that a problem or defect exists; catastrophic failures are obvious, but gradual failures might not be noticed for some time.
2. Quickly locating and identifying the defective component; the solution to this problem includes
 - good training,
 - good instrumentation panels, and
 - appropriate test apparatus.
3. Rectifying the defective component, which could include finding replacement parts.
4. Verifying that the repaired system functions correctly.

13.DESIGNING FOR MAINTENANCE

A survey among building services engineers revealed that maintenance requirements were addressed before the detailed design stage in less than 50% of projects. Maintenance can be preventive or corrective. Preventive maintenance, also called time-based maintenance, requires a defined routine of activities such as cleaning, lubricating, replacement of filters, etc. Measurement of critical parameters might also be performed to detect early signs of component failure. Corrective maintenance can be either planned or unplanned. Planned corrective action would be initiated following discovery of a defect during a routine inspection. Unplanned maintenance results from failure of the equipment; it is often referred to as a “run to failure” policy. This strategy is more difficult to manage because human power and spares requirements are very difficult to predict and can result in excessive downtime and poor equipment availability.

For an electrical installation that supplies critical loads, it is essential that the system be designed with maintainability in mind and that the maintenance strategy is well planned. Individual items of equipment will need to be serviced, tested, and calibrated, or even replaced entirely, without disturbing the load. This will be possible only if redundant units and/or bypass links have been provided.

14.COST VERSUS RELIABILITY

Introducing increased reliability and maintainability into a design will increase the initial capital costs, but this increase will be offset against savings from reduced maintenance costs and reduced costs of failure. Savings arise not only from a reduction in the work hours required for maintenance but also because of a reduction in the on-site spares stocks required.

Experience has taught us that the capital cost rises and the cost of maintenance falls as the target system MTBF increases. The optimum design, from a purely economic point of view, occurs when the total of capital and maintenance costs is at a minimum.

When there are other risks associated with the loss of power, the potential cost of a power failure can be extremely high, as in the case of a critical operational data center and PPS. The likely costs can be several times the capital cost of the installation, so the cost of providing an installation with increased reliability and resilience becomes insignificant in comparison.

15.RELIABILITY AND SAFETY

When designing any power system under the new Construction Design and Maintenance (CDM) regulations (OSHA and NEC), safety will be an important factor. It is worth acknowledging that safety and reliability can conflict. This can happen when safety considerations require the introduction of additional complexity, such as the provision of safety interlocks, which reduces reliability. Safety must always take precedence, and additional steps will be required to maintain the required reliability.

16.SNS ELECTRICAL POWER RELIABILITY ASSESSMENT

In lieu of the previously stated criteria for reliability assessment, the SNS project has chosen electrical power distribution design as follows:

- Two independent 161-kV feeds from TVA—reliability very good.
- Two 47.5-MVA transformers with a tie breaker on the 13.8-kV secondaries—reliability good.
- Radial (star configuration) feed to substations and RF transformers (chosen over loop feed as a cost-preserving mean)—cable failures on a 13.8-kV are distribution rare—reliability considered good.
[Underground utilities (e.g., cable duct banks) are designed for radial feed, and upgrade at this point would delay the project by six months; later upgrade would disrupt the accelerator operation for at least ten months to one year.]
- Loop feed for CHL compressors—reliability excellent.
- Generator: UPS redundancy for computer communications and PPS—reliability excellent.
- Generator redundancy to support emergency operations (safety)—reliability excellent.
- Separation of linear and nonlinear loads and placement on different transformers on the LV side.
- Evaluation of K-factor transformers for nonlinear loads to prevent transformer losses and neutral conductor overheating.
- Implementation of harmonic filters.
- Specification of connected equipment to comply with IEC 61000 (flicker, harmonics, etc.).
- Maintenance (an important part of reliability of the system that cannot be omitted in reliability assessment).
- Careful choice of equipment manufacturer and assessment of spare parts availability, which is crucial for accelerator systems reliability.